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RELATION BETWEEN SPECIFIC HEAT AND EMISSIVITY OF TANTALUM AT ELEVATED TEMPERATURES

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(Prepared under Contract No. AF 33(616)-7123 by
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FOREWORD

This report was prepared by the University of Cincinnati under Contract No. AF 33(616)-7123. This research was carried out under Project No. 7367, "Research on Characterization and Properties of Materials," Task No. 736704, "Extreme High Temperature Research Studies, Techniques, and Measurements." The work was administered under the direction of the **Air Force Materials Laboratory Deputy Commander/Research and Engineering,** Aeronautical Systems Division, with Mr. Hyman Marcus acting as Project Engineer.

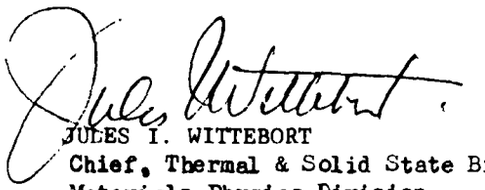
This report covers work conducted from July 1961 to December 1962.

ABSTRACT

The rate of cooling in vacuum of tantalum cylinders of various sizes has been studied in the temperature range 1850° to 1300°K. The ratio of specific heat, C_p, to total emissivity, ε, was found to be constant:

$$\frac{C_p}{\varepsilon} = 0.226 \pm .004 \text{ cal/gm/°K.}$$

This technical documentary report has been reviewed and is approved.



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LIST OF SYMBOLS

$\dot{q}_1$	power input to the specimen
$\dot{q}_g$	thermal energy gain of the specimen
$\dot{q}_\gamma$	radiation loss of the specimen
σ	Stefan Boltzmann constant
A	area of the sample at temperature T
T	black-body temperature of the sample
T_o	temperature of the surroundings to which energy is radiated
$F(\varepsilon\varepsilon_o)$	a function of the total emissivities of the body and surroundings respectively
m	mass of the sample
C_p	specific heat at temperature T
θ, θ'	time in seconds
α	first coefficient of linear thermal expansion
β	second coefficient of linear thermal expansion
T'	T - 300
f, f_2, f_3, f_4	analytical functions
a,b,c,d	constants
ε	total emissivity
κ	thermal conductivity

I. INTRODUCTION

With recent advances in science and technology considerable attention has been focused on the determination of the specific heat of solids and its temperature dependence, because of the fundamental importance of this thermal property in understanding the physics of solids, and also in assessment of the performance of solid materials when subjected to high temperatures.

Recent investigations in the experimental determination of the specific heats of solids show a notable emphasis on the transient techniques, particularly for measurements at elevated temperatures, compared to the conventional calorimetric methods.

Compared to the calorimetric methods, the transient techniques have the advantages of speed and simplicity and do not need the knowledge of the thermodynamic properties of a standard or a reference substance.

Transient techniques are based upon the statement of a thermal power balance. By equating the sensible heat gain or loss in unit time to the net input or loss at a given steady state temperature, the power balance can be solved for the specific heat.

A special version of this technique is one where the specimen loses heat from the surface to the surroundings by radiation. The power balance in this case is the well known Stefan Boltzmann Law and the specific heat can be evaluated by knowing the instantaneous cooling rate and the total emissivity of the specimen.

The present study aims at an improvement in the radiometric method by the adaptation of the Radiation Electronics Corporation Thermodot (Model TD-1) coupled with continuous recorders (Leeds and Northrup Speedomax Type G recorders,

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Model 5-6000 Series) which, by mapping the continuous cooling curves, enable one to obtain point values of $\frac{dT}{d\theta}$ so that measurements of specific heats of higher accuracy and reproducibility than hitherto possible can be obtained in a much simpler way.

As will be seen later, this method gives the ratio of specific heat to total emissivity. At the outset the aim was to determine the specific heat using known values of the emissivity. Checking the literature carefully, it was found that the total emissivity is known much less accurately than the specific heat. This method thus should be more suitable to obtain emissivities.

II. THEORY

When a sample is heated to a high temperature in a vacuum and if q_1 is the power input to the specimen, $\dot{q}_g$ the thermal energy gain of the specimen, and $\dot{q}_\gamma$ the radiation loss, then the instantaneous power balance can be written as:

$$\dot{q}_1 = \dot{q}_g + \dot{q}_\gamma \tag{1}$$

According to the Stefan Boltzmann Law

$$\dot{q} = \text{Radiation Loss} = \sigma F(\varepsilon\varepsilon_o)A(T^4 - T_o^4) \tag{2}$$

where

σ = Stefan Boltzmann constant

A = area of the sample at temperature T

T = black-body temperature of the sample

T_o = temperature of the surroundings to which energy is radiated

$F(\varepsilon\varepsilon_o)$ = a function of the total emissivities of the body and surroundings, respectively.

The thermal energy gain is:

$$\dot{q}_g = m \cdot C_p \frac{dT}{d\theta} \tag{3}$$

where

m = mass of the sample

C_p = specific heat at temperature T

$\frac{dT}{d\theta}$ = instantaneous value of the slope of the time-temperature curve at temperature T.

Therefore, from Eqs. (1), (2), and (3)

$$\dot{q}_1 = m \cdot C_p \frac{dT}{d\theta} + \sigma F(\varepsilon\varepsilon_o)A(T^4 - T_o^4) \tag{4}$$

Techniques for the determination of C_p, based upon Eq. (4), require the precise knowledge of the instantaneous power input $\dot{q}_1$.

The techniques based upon Eq. (4) are subject to certain limitations in the precise evaluation of the instantaneous power input (e.g. due to heat losses through leads), etc. which tend to complicate the analysis of the data.

Hence, the trend in recent investigations shows a definite emphasis on the transient techniques which are adapted to the case where $\dot{q}_1 = 0$; where the specimen is heated to an elevated temperature in a vacuum and is allowed to cool. The instantaneous cooling rate of the sample is measured while it is losing heat by radiation from its surface.

When $\dot{q}_1 = 0$

$$m \cdot C_p \frac{dT}{d\theta} = -\sigma F(\varepsilon\varepsilon_o)A(T^4 - T_o^4) \tag{5}$$

When $T \gg T_o$

$$m \cdot C_p \frac{dT}{d\theta} = -\sigma F(\varepsilon\varepsilon_o)AT^4 \tag{6}$$

The determination of C_p by Eq. (6) implies that internal gradients are small enough to be neglected, and that the assumption of a purely radiative loss of heat is adequately satisfied.

The function $F(\varepsilon\varepsilon_o)$ depends upon the total emissivities ε and ε_o and on the relative configuration of specimen and environment. The geometry employed in this study is that of a cylindrical body of finite length radiating partially to an open helix a small distance away, and partially to a

closed concentric shell of radius large compared with that of the specimen. This configuration may be regarded as intermediate between the case of a completely enclosed body large compared to the dimensions of the enclosure, and that of a body small compared to the dimensions of the enclosure. For the first case, Hottel[1] gives the expression

$$F(\varepsilon, \varepsilon_o) = \frac{1}{\frac{1}{\varepsilon} + \frac{1}{\varepsilon} - 1} \tag{6'}$$

for the second,

$$F(\varepsilon, \varepsilon_o) = \varepsilon \tag{6''}$$

It is seen that if $\varepsilon_o = 1$, i.e. if the surroundings are made perfectly black, Eq. (6') reduces to (6'') so that the emission function is essentially unaffected by the proximity of the coil.

Therefore, Eq. (6) reduces to

$$m \cdot C_p \frac{dT}{d\theta} = -\sigma \varepsilon A T^4 \tag{7}$$

Rearranging Eq. (7)

$$m \cdot C_p \frac{dT}{T^4} = -\sigma \varepsilon A d\theta \tag{8}$$

$$\frac{C_p}{\varepsilon} \cdot d\left(\frac{1}{T^3}\right) = \left(\frac{3\sigma A}{m}\right) d\theta \tag{9}$$

$$\frac{C_p}{\varepsilon} \cdot \frac{d(1/T^3)}{d\theta} = \frac{3\sigma A}{m} \tag{10}$$

where

$$\frac{C_p}{\varepsilon} = g(T), \text{ some function of temperature}$$

$\frac{d(1/T^3)}{d\theta}$ = slope of the curve between $1/T^3$ vs. θ

$A \cong A_o[1 + 2\alpha(T - 300) + 2\beta(T - 300)^2]$, where α and β are the first and second coefficients of linear thermal expansion.[2] (11)

A_o = surface area of the specimen at room temperature.

From Eq. (10)

$$\frac{C_p}{\varepsilon(1 + 2\alpha T' + 2\beta T'^2)} \cdot \frac{d(1/T^3)}{d\theta} = \frac{3\sigma A_o}{m} \tag{12}$$

where

$$T' = (T - 300) \tag{13}$$

Either Eq. (7) or (12) can be used to obtain C_p. In using Eq. (7), $T = f_1(\theta)$ (14) or $\theta = f_2(T)$ (14a), has to be obtained. Using Eq. (12), $1/T^3 = f_3(\theta)$ (15) or $\theta = f_4(1/T^3)$ (15a), has to be evaluated. When choosing the functions f_1, f_2, f_3, and f_4, due regard has to be paid to the physical requirements of this decay phenomena in which T and $dT/d\theta$ are continuous and smoothly decreasing functions of θ. At any interval of time θ neither T nor $dT/d\theta$ can contain any discontinuities, maxima, minima or points of inflection.

Furthermore, the origin of the time scale can be shifted without affecting the shape of the cooling curve. A change of θ to $\theta + \theta'$ must shift each point parallel to the θ axis by an amount θ'. This is done easily if Eqs. (14a) or (15a) are used.

The decision, which equations, (7) and (14a), or (12) and (15a) are used is made on the ground that Eq. (15a) will be simpler and easier to differentiate than Eq. (14a). In Eq. (12), C_p and ε are both monotonously and slowly increasing with temperature,[3,4,5] the expression $(1 + 2\alpha T' + 2\beta T'^2)$

changes only 2% between 300° and 2000°K, the right hand side is a constant; thus $\frac{d(1/T^3)}{d\theta}$ will only vary little with temperature, and its evaluation made easy. Using Eq. (7), $-\frac{dT}{d\theta}$ will vary approximately as T^4, making its evaluation difficult. The functional form used will be:

$$a + b\theta = \frac{1}{T^3} + c\left(\frac{1}{T^3}\right)^2 + d\left(\frac{1}{T^3}\right)^3 + \ldots \qquad (15b)$$

Measurements of C_p based upon Eq. (7) or (12) require:

a) Precise knowledge of total emissivity and its temperature dependence.

b) Knowledge of variation of A with temperature.

c) Mapping of the cooling curve.

III. EQUIPMENT AND INSTRUMENTATION

1. Heating Chamber and Vacuum System

The heating chamber used in these measurements is cylindrical (11-3/4 in. height; 6-1/8 in. I.D.) made of 40:60 brass using silver brazing for connecting side arms, side ports, and flanges (Fig. 1). The power leads (two copper tubings of 1/4 in. diameter) enter the chamber via rubber glass compression seals and are connected to a copper work coil.

A heating coil, made up of 1/4 in. diameter copper tubing, 7-3/4 in. length, 1-1/2 in. internal diameter, and having 34 turns, is installed within the system concentric with the heating chamber.

The three sight ports of the heating chamber are closed with 0.33 cm. thick optical flats of Pyrex seated on neoprene "o" rings. The chamber walls and top are cooled by water running through soft-soldered copper coils.

The vacuum system, connected to the chamber by a copper pipe (2 in. diameter; 8 in. length), consists of a Veeco CT-200 2 in brass cold trap, an NRC H-4-P diffusion pump Type 137 and a Welch Duo-Seal mechanical pump.

The fore vacuum is read by a Veeco thermocouple gauge, and the chamber vacuum by a Veeco DG-2 cold cathode discharge gauge.

2. Power Supply

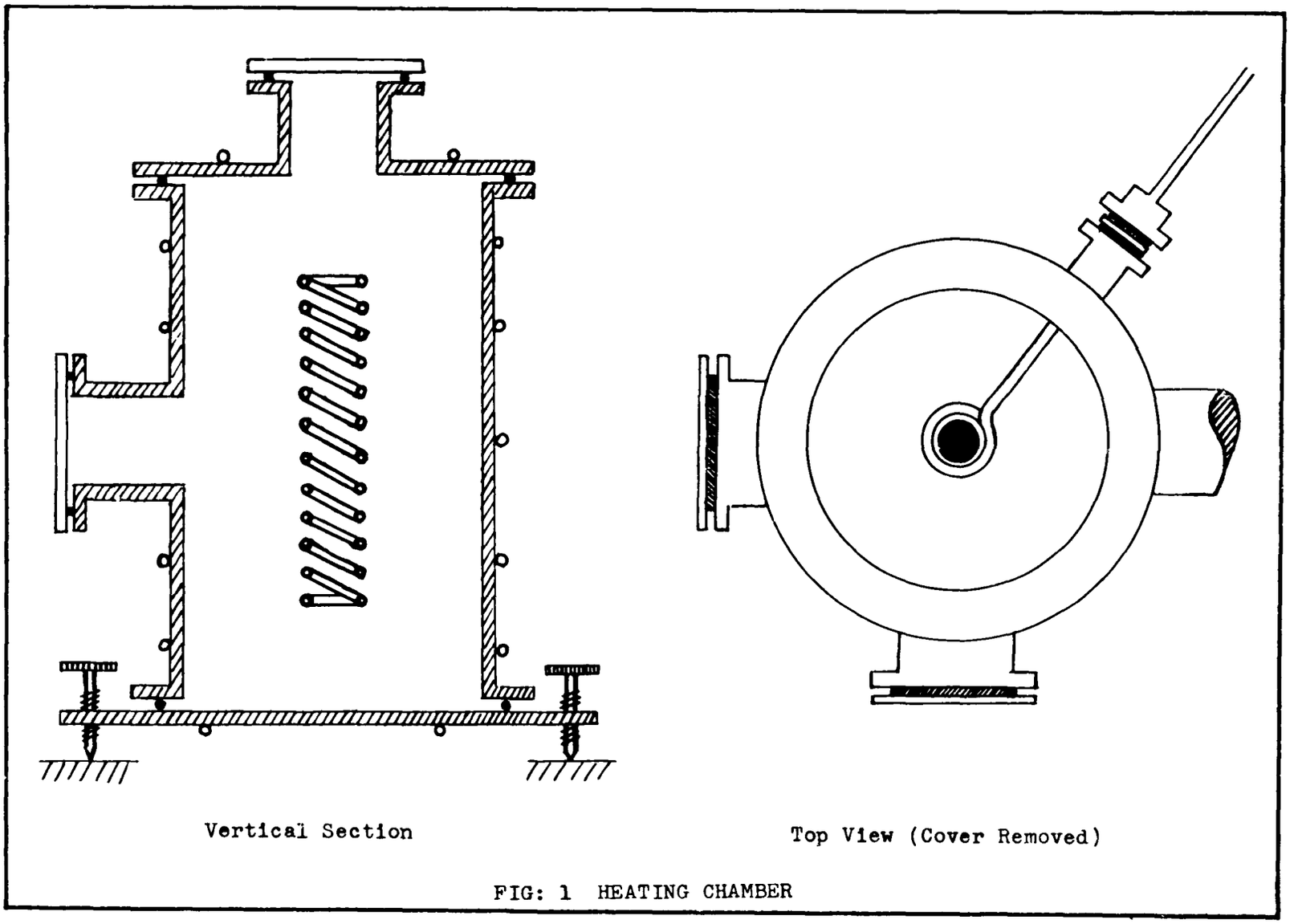
Thermionic Generator (Induction Heating Corporation), Model 1070, 20 KW.

3. Radiation Thermometer

Radiation Electronics Corporation Thermodot TD-1, Serial No. 1010. High temperature aperture plate removed.

4. Temperature Measuring Device

Disappearing filament optical pyrometer (Leeds and Northrup), Serial



Vertical Section

Top View (Cover Removed)

FIG: 1 HEATING CHAMBER

No. 371189 with a maximum range of 5200°F and calibrated in accordance with the 1948 International Temperature Scale.

5. Recorder

Speedomax Type G recorder (Leeds and Northrup), Model 5-6000 Series, operated at a chart speed of 1/2 in. per second during this investigation.

6. Timer

A timer (Kramer Timer Corporation), Model 511, providing signals for every two seconds to an accuracy of 1° per rotation.

IV. EXPERIMENTAL PROCEDURE

1. Specimens and Their Arrangement

The specimens used were tantalum rods obtained from the Fansteel Metallurgical Corporation. Three samples of different sizes were used during this investigation. Their properties are given in Table 1. Samples 2 and 3 were obtained in 1958, Sample 1 in 1961. Thus the danger of using material from a special batch does not exist.

One-sixteenth inch transverse holes were drilled through Samples 1 and 2 and 3/32 in. transverse holes through Sample 3. The holes were drilled at 7/32 in. from one end in Samples 1 and 2 and at 5/32 in. from one end in Sample 3.

Tantalum wire (0.025 in. diameter) was run through the hole in the sample and up to a suspension ring seated within the flange of the upper sight port of the heating chamber so that the sample was suspended within the coil concentric to it. The suspension was a four-point 2-V Type suspension.

After mounting the sample, the sight ports were closed and the heating chamber evacuated to a pressure below 10^{-5} mm. Hg. Then a better vacuum level was obtained by circulating hot water through copper tubes soldered to the chamber for a long interval of time and then by filling the cold trap with liquid nitrogen.

The sample was heated slowly until the maximum attainable temperature was reached. Extended outgassing was done for long intervals of time to insure that residual gases, if any, were reduced to a basic minimum. Then the calibration run was started.

TABLE 1

Dimensions and Weights of the Samples

Sample 1

length = 4.0350 in.

diameter = 0.5000 in.

area = 6.7339 sq. in. = 43.4444 $cm.^2$

mass = 215.013 gm.

$K = \left(\frac{3\sigma A_o}{m}\right) = 0.82199 \times 10^{-12}$ cal/sec/gm/$°K^4$

Sample 2

length = 3.9963 in.

diameter = 0.4945 in.

area = 6.5950 sq. in. = 42.5483 $cm.^2$

mass = 208.113 gm.

$K = \left(\frac{3\sigma A_o}{m}\right) = 0.83173 \times 10^{-12}$ cal/sec/gm/$°K^4$

Sample 3

length = 1.7440 in.

diameter = 0.2501 in.

area = 1.4690 sq. in. = 9.4774 $cm.^2$

mass = 22.903 gm.

$K = \left(\frac{3\sigma A_o}{m}\right) = 1.68343 \times 10^{-12}$ cal/sec/gm/$°K^4$

2. Temperature Calibration

If the emitting surface is grey in the spectral sensitivity region, a Thermodot can be utilized for the evaluation of the black-body temperature. Metals which emit selectively over broad spectral regions are not truly grey.

The high temperatures attained during this investigation preclude the possibility of any coating.

For the reasons stated above, the response of the recorder is correlated to an absolute temperature instrument, in this case, a Leeds and Northrup disappearing filament optical pyrometer. The pyrometer is focused through the top viewing port onto the upper surface of the suspended sample in such a manner that the disappearing filament nearly coincides with the tangent to the circular periphery.

The optical head of the Thermodot is focused onto the cylindrical surface of the sample through one of the lateral sight ports of the chamber. The minimum distance between the object and the optical head is 4 ft., as suggested by the manufacturer. Any small variations in the distance between the optical receiver and the object does not affect the results, although it is imperative that for each setting precise focusing and calibration be done separately. The focusing is done by viewing through the antiparallax telescopic sight, such that the adjustments give a maximum signal reading on the Thermodot dial.

The output of the Thermodot is fed to the recorder. The optical receiver is arranged at a suitable position, and after selecting the full scale signal position and function selector of the Thermodot suitably, the millivolt range of the recorder is adjusted such that the recording pen always lies with the range of scale for a particular temperature interval of study. Precise adjustment for balancing, amplification, and sensitivity are

basic requirements for the reproducibility of results.

Improper adjustment of the amplification of the recorder provides a discontinuous cooling curve due to jerky movements of the recording pen while no amplification leads to complete insensitivity of the recording pen for temperature changes. When properly adjusted the recording pen provides a smooth, continuous cooling curve.

Also, the sensitivity of the recorder has to be adjusted for optimum conditions of performance. Too low a sensitivity leads to no or little response from the recording pen for any temperature changes, while too high a sensitivity leads to the uncertainty of locating the position of the recording pen during calibration.

With the optical receiver of the Thermodot properly focused, the level of the output signal of the Thermodot well adjusted, and the sensitivity and amplification of the recorder adjusted for optimum conditions of performance, the sample is held at a steady-state temperature and the corresponding position of the recording pen is recorded and the temperature is determined accurately at least six times to provide an adequate basis for statistical average. The measured temperature which corresponds to the surface temperature of the sample is corrected for glass absorption and for non-black-body conditions. The corrections for surface temperature to true temperature are obtained from the data of Malter and Langmuir.[4]

Since the pyrometer is used as an absolute temperature instrument in this investigation, the distance over which the recording pen moves in covering a certain temperature interval of study is properly matched to the distance over which the pyrometer drum moves to cover the same temperature interval for optimum performance.

3. Mapping the Cooling Curve

Having done the calibration in the manner described above, the sample is heated to the highest attainable temperature and held at that temperature for several minutes to insure the attainment of a true steady state. Then the chart motor and the timer are started, the furnace is shut off, and the cooling curve is traced. A typical cooling curve is shown in Fig. 2.

4. Evaluation of C_p

From the cooling curve, i.e. the temperature-time relationship, $1/T^3$ is plotted versus θ, and the coefficients in Eq. (15a) obtained. By differentiation $\frac{d(1/T^3)}{d\theta}$ is obtained. This, combined with the literature values of ε[3,4,5] and the expansion coefficient,[2] gives C_p.

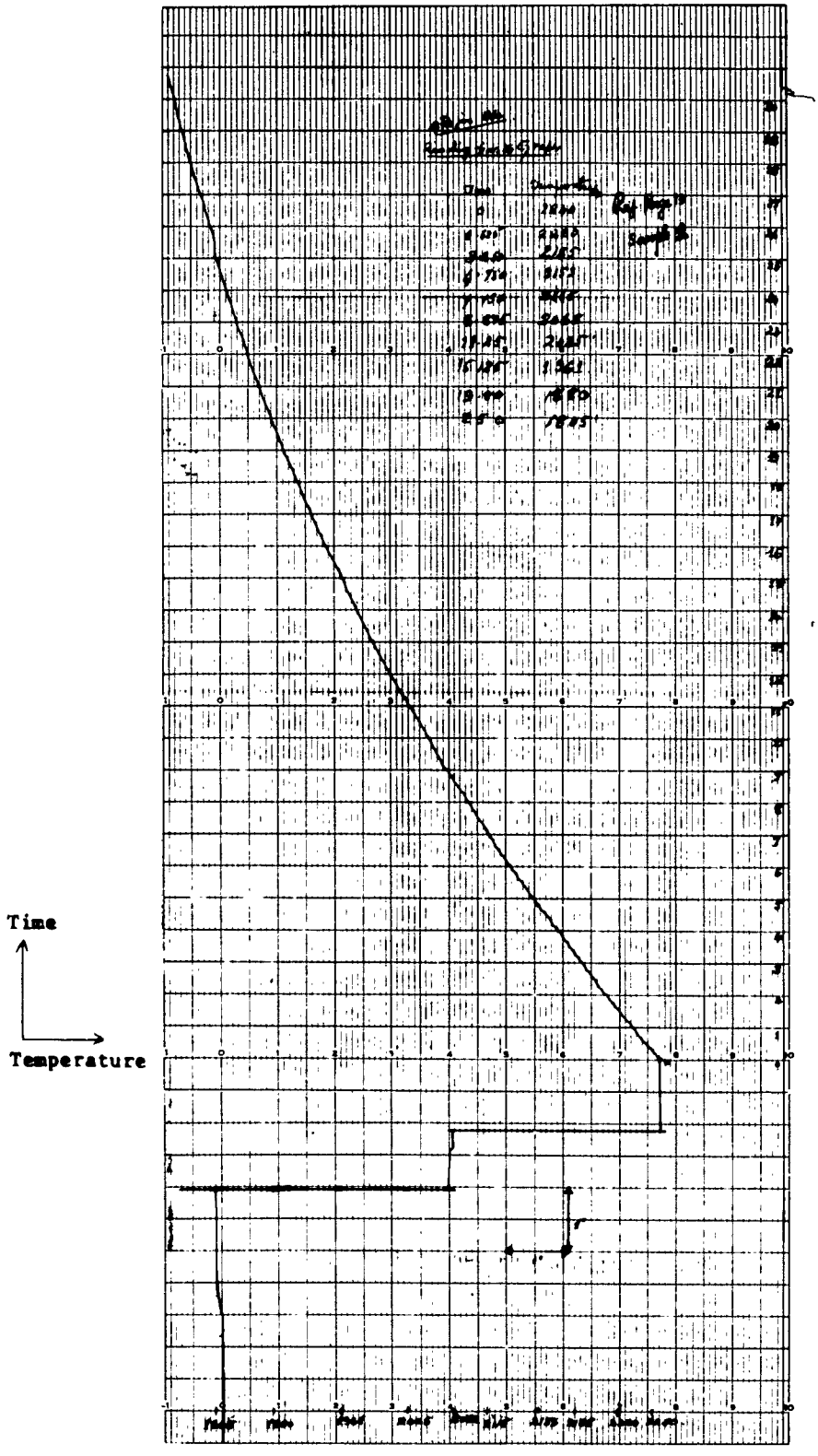


Figure 2. A Typical Cooling Curve

V. EXPERIMENTAL RESULTS AND DISCUSSION OF DATA

To obtain a uniform "equilibrium" surface, all the samples were heated in high vacuum for 1 hr. at 2250°K and for 1/2 hr. at 2350°K before the measurements were taken. This was the maximum temperature attainable without overheating the heating chamber.

The various temperature-time data obtained are given in Tables 2 to 6. A plot of $1/T^3$ vs. θ is, for all samples, within experimental error a straight line. The coefficients c and d are zero in Eq. (15b). Thus the experimental data can be represented as

$$\frac{1}{T^3} = a + b\theta \tag{16}$$

On the bottom of each table a and b are evaluated by least squares using an IBM 1620 computer; the error limits are one standard deviation. In all cases the correlation coefficient was greater than 0.999.

Combining Eq. (16) with Eq. (12),

$$\frac{C_p}{\varepsilon(1 + 2\alpha T' + 2\beta T'^2)} = \frac{3\sigma A_o}{mb} \tag{17}$$

the right hand side of Eq. (17) is a constant; thus the left hand side is also. As the expression in the bracket varies only 2% between 300° and 2000°K, C_p/ε is constant. For simplicity $\varepsilon' = \varepsilon(1 + 2\alpha T' + 2\beta T'^2)$. Thus

$$\frac{C_p}{\varepsilon'} = \frac{3\sigma A_o}{mb} \tag{17a}$$

The value of C_p/ε' given by Eq. (17a) from the data of Tables 2 to 6, is given in Table 7. The values of $3A_{oi}/m_i b_i$ (where i = 1, 2, and 3) are the same for all the samples.

TABLE 2

Cooling Data on Sample 1

Sample 1

Temp. T°K	Time θ sec.
1712	0
1687	2.50
1664	5.25
1631	8.0
1605	11.50
1583	14.375
1550	19.125
1515	24.625
1475	32.40

$a = (2.0046 \pm 0.0056)10^{-10}$

$b = (3.5034 \pm 0.0550)10^{-12}$

TABLE 3

Cooling Data on Sample 1

Sample 1

Temp. T°K	Time θ sec.
1842	0
1829	1.10
1804	2.40
1775	4.80
1743	7.40
1709	9.60
1680	13.70
1647	17.35
1621	20.525
1583	24.775
1529	32.10

$a = (1.6101 \pm 0.0047)10^{-10}$

$b = (3.6817 \pm 0.0471)10^{-12}$

TABLE 4

Cooling Data on Sample 2

Sample 2

Temp. T°K	Time θ sec.
1832	0
1809	1.60
1788	3.00
1764	5.00
1737	7.30
1715	9.40
1687	12.20
1645	16.55
1621	19.325
1570	26.00

$a = (1.6349 \pm 0.0016)10^{-10}$

$b = (3.6760 \pm 0.0201)10^{-12}$

TABLE 5

Cooling Data on Sample 3

Sample 3

Temp. T°K	Time θ sec.
1741	0
1725	0.85
1697	2.00
1672	3.20
1627	5.50
1550	10.15
1487	15.20

$a = (1.89440 \pm 0.00367)10^{-10}$

$b = (7.6298 \pm 0.07144)10^{-12}$

TABLE 6

Cooling Data on Sample 3

Sample 3

Temp. T°K	Time θ sec.
1676	0
1632	1.85
1608	3.20
1580	4.60
1540	6.50
1486	10.00
1462	11.80
1434	13.90
1388	18.90
1348	24.10
1297	33.70

$a = (2.2259 \pm 0.0292)10^{-10}$

$b = (7.5168 \pm 0.3022)10^{-12}$

TABLE 7

Evaluation of $\frac{C_p}{\varepsilon[1 + 2\alpha(T - 300) + 2\beta(T - 300)^2]}$

Sample	Temperature Range °K	Number of Points	$\frac{C_p}{\varepsilon[1 + 2\alpha(T - 300) + 2\beta(T - 300)^2]}$ cal/gm/°K
1	1712-1475	9	0.2346 ± 0.0036
1	1842-1529	11	0.2233 ± 0.0029
2	1832-1570	10	0.2263 ± 0.0012
3	1741-1487	7	0.2206 ± 0.0020
3	1676-1297	11	0.2240 ± 0.0087

From the results at the bottom half of Table 7, it could be seen that, independent of sample size and origin, the values of C_p/ε' agree very well.

In each run the variation of the slope of the straight line due to any scatter of the experimental data was found to be within a few per cent. The maximum scatter, 3.82%, was found in Sample 3 during the lower half of the temperature range of study. The scatter at these temperature ranges of study was due to the instability of the furnace at certain temperature ranges which led to small fluctuations in the position of the recording pen. No such larger scatter was found during the run in the upper half of the temperature range of study. The minimum scatter was found in the case of Sample 2, which was about 0.5%.

The radial temperature gradient in the sample can be estimated by equating conduction and radiation heat transfer at the sample surface. That is, $\kappa \frac{\partial T}{\partial r}$ = heat transfer per unit area by radiation, where κ is thermal conductivity. At the highest temperature involved $\frac{\partial T}{\partial r} \simeq 40°K/cm$. If the gradient were assumed linear across the 1/2 in. diameter sample, there would be a difference from center to surface of 25°C. Considering that the temperature gradient must become zero at the center, the actual gradient is less, and the average temperature of the sample would be within a few degrees of the surface temperature. Because the specific heat changes so slightly with temperature, this is a negligible error.

The values of C_p/ε obtained during this investigation are compared with the values of C_p/ε computed from data obtained in the literature in the following way.

The values of C_p obtained by calorimetric methods are taken from the literature.[6,7] The values of C_p obtained by thermionic techniques are also used.[3]

The values of ε reported in the literature are taken.[4,5] Then C_p/ε values are determined for different possible groupings of values of C_p and ε. The values of C_p/ε so calculated are given in Tables 8, 9, 10, and 11. In each case the data sources for C_p and ε are given. The values of ε reported[4] are the values of total normal emissivity. Also, the data for C_p and ε[3,4] were from the same source.

The values of C_p/ε' obtained during this investigation are slightly higher compared to those obtained by methods outlined above showing that the samples used during this investigation have a true and brighter surface.

This observed discrepancy probably has its origin in the difference in the purity level, surface condition, and surface treatments - a conclusion arrived at by some authors[2] during their studies of other physical properties of this metal.

Regarding the constancy of C_p/ε', as is well known, it is dependent upon the temperature dependences of C_p and ε. To compare the values of C_p/ε' obtained during this investigation with those given in Tables 8 to 11, it would be instructive to consider the values computed from the data of Malter and Langmuir[3,4] since the values of C_p and ε are determined for the same type of samples. These values are given in Table 10. The values of C_p/ε given in Table 10 agree with those obtained in this investigation, although a small variation of C_p/ε with temperature can be found in the results given in Table 10. This is probably because of the strong temperature dependence of ε. Utterbach and Sandermann,[8] while comparing the results of their power radiation data with Worthing's data,[9] which agree with Malter and Langmuir's data,[4] arrived at the same conclusion regarding the temperature dependence of ε.

From the considerations given above, it could be inferred that the

TABLE 8

Calculation of $\frac{C_p}{\varepsilon}$ by Combination of C_p and ε Data

Temp. °K	Emissivity[4]	$(C_p \times 10^2)$[6] cal/gm/°K	(C_p/ε)
1000	0.136	3.6488	0.2683
1100	0.144	3.6920	0.2564
1200	0.153	3.7351	0.2441
1300	0.163	3.7782	0.2318
1400	0.174	3.8213	0.2196
1500	0.184	3.8644	0.2100
1600	0.194	3.9076	0.2014
1700	0.205	3.9507	0.1927

TABLE 9

Calculation of $\frac{C_p}{\varepsilon}$ by Combination of C_p and ε Data

Temp. °K	Emissivity[5]	$(C_p \times 10^2)$[6] cal/gm/°K	(C_p/ε)
1422	0.0854	3.8328	0.4488
1339	0.0829	3.7950	0.4578
1283	0.0835	3.7709	0.4516
1269	0.0811	3.7648	0.4642
1172	0.0811	3.7230	0.4591
1130	0.0726	3.7049	0.5103
1116	0.0665	3.6989	0.5562
1089	0.0616	3.6872	0.5986
991	0.0640	3.6449	0.5695
950	0.0598	3.6273	0.6066
936	0.0543	3.6212	0.6669
922	0.0530	3.6152	0.6821
866	0.0500	3.5910	0.7182
839	0.0500	3.5794	0.7159
783	0.0500	3.5553	0.7111
700	0.0457	3.5195	0.7833
672	0.0463	3.5074	0.7515
616	0.0433	3.4832	0.8044
450	0.0311	3.4117	1.0970

TABLE 10

Calculation of $\frac{C_p}{\varepsilon}$ by Combination of C_p and ε Data

Temp. °K	Emissivity^4	$(C_p \times 10^2)^3$ cal/gm/°K	(C_p/ε)
1500	0.1740	3.9150	0.2250
1550	0.1790	3.9575	0.2211
1600	0.1840	4.0000	0.2174
1650	0.1890	4.0425	0.2139
1700	0.1940	4.0850	0.2106
1750	0.200	4.1275	0.2064
1800	0.215	4.1700	0.1940
1850	0.219	4.2125	0.1924
1900	0.223	4.2550	0.1908
1950	0.228	4.2975	0.1885
2000	0.232	4.3400	0.1871
2050	0.236	4.3825	0.1857
2100	0.240	4.4250	0.1844
2150	0.244	4.4675	0.1831
2200	0.247	4.5100	0.1826
2250	0.251	4.5525	0.1814
2300	0.254	4.5950	0.1809
2400	0.261	4.6800	0.1793
2600	0.276	4.8500	0.1757
2800	0.288	5.0200	0.1743

TABLE 11

Calculation of $\frac{C_p}{\varepsilon}$ by Combination of C_p and ε Data

Temp. °K	Emissivity[4]	$(C_p \times 10^2)$[7] cal/gm/°K	(C_p/ε)
1273	0.1600	3.7530	0.2341
1323	0.1650	3.7645	0.2277
1373	0.1685	3.7820	0.2244
1423	0.176	3.7935	0.2155
1473	0.181	3.8080	0.2100
1523	0.186	3.8225	0.2055
1573	0.191	3.8400	0.2001
1623	0.196	3.8515	0.1965
1673	0.201	3.8660	0.1923
1723	0.207	3.8835	0.1875
1773	0.213	3.8980	0.1833
1823	0.217	3.9125	0.1805
1873	0.221	3.9270	0.1777
1923	0.225	3.9415	0.1752

small variation of C_p/ε with temperature, as could be seen from Table 10, is probably due to an error in radiation data and C_p/ε is indeed a constant independent of temperature interval of study.

Recent data of Betz et al.[5] refer to the total normal emissivity which may be 10 to 15% lower than the total hemispherical emissivity required in the calculations. Even giving due consideration to this, the values of ε reported[5] are much smaller when compared to Malter and Langmuir's,[4] and hence, is the reason for the high values of C_p/ε obtained by using Betz et al.'s data.[5] This is given in Table 8. The small variation of ε[5] is also responsible for the large temperature dependence of C_p/ε as could be seen from Table 9. Hence, only use of the hemispherical emissivity data of recently produced tantalum to compute C_p/ε values justifies comparison with the values obtained during this investigation for the purposes of determining the constancy of C_p/ε', a fact proved decisively without the use of the actual value of ε.

VI. REFERENCES

1. A. J. Brown and S. M. Marco, "Introduction to Heat Transfer," McGraw-Hill Book Co., New York, p. 61, 1951.

2. J. Edwards, R. Speiser, and H. L. Johnston, J. Appl. Phys., 22, 425 (1951).

3. L. Malter and D. B. Langmuir, Phys. Rev., 55, 1138 (1939).

4. L. Malter and D. B. Langmuir, Phys. Rev., 55, 743 (1939).

5. E. T. Betz et al., WADC Technical Report 56-222, Part II (1957).

6. K. K. Kelley, U.S. Bureau of Mines Bulletin 476 (1949).

7. M. Hoch and H. L. Johnston, J. Phys. Chem., 65, 855 (1961).

8. C. L. Utterbach and L. A. Sandermann, Phys. Rev., 39, 1008 (1932).

9. A. G. Worthing, Phys. Rev., 28, 174 (1926).

Aeronautical Systems Division, AF Materials Lab, Materials Physics Division, Wright-Patterson AFB, Ohio.
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$$\frac{C_p}{\varepsilon} = 0.226 \pm .004 \text{ cal/gm/°K.}$$

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